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The SSPX Thermistor System

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The SSPX Thermistor is a glass encapsulated bead thermistor made by Thermometrics, a BR 14 P A 103 J . The BR means ruggedized bead structure, 14 is the nominal bead diameter in mils, P refers to opposite end leads, A is the material system code letter, 103 refers to its 10 kΩ zero-power resistance at 25° C, and the tolerance letter J indicates ± 5% at 25° C. It is football shaped, with height ➵, and is viewed through a slot of height h = 0.01 inches. The slot is perpendicular to the long axis of the bead, and is a distance s ≈ 0.775 cm in front of the thermistor. So plasma is viewed over a large angle along the slot, but over a small angle α perpendicular to the slot. The angle α is given by $2s\tan\alpha =$ ➵ $+ h$.

The slot is a distance d (≈ 10 cm) from the plasma edge (plasma radius a = 50 cm) so the integral for the power on the thermistor front surface area is[1]

$$P_{det} = \int_0^{2a} dx \frac{p}{4\pi r^2} \int_0^{\alpha} 2r d\phi \int_0^{\theta_1} A(\phi) 2r d\theta$$

Here the radiated power density p is assumed constant in the plasma being viewed, $\cos\theta_1 = \frac{r^2 + (a + d)^2 - a^2}{2r(a + d)}$, and $A(\phi) = A_{det}(1 -$

Error!

$$P_{det} = \frac{\alpha p}{2\pi} A_{det} \int_0^{2a} \theta_1 dx = \frac{\alpha a p}{2\pi} A_{det} \int_0^{2} \theta_1(u) du$$

where r = x + d, x = au, and d = ba and $\cos\theta_1 = \frac{u(u + 2b) + 2b(1 + b)}{2(u + b)(1 + b)}$. With b = 1/5 we find $\int_0^2 \theta_1 du = 1.472$, and using ➵ $= 2\zeta$ for our thermistor, we have

$$2.72sP_{det} = pa\zeta^3(\text{⧟} + \frac{h}{2\zeta}) = 1.357pa\zeta^3 \qquad \text{W/m}^2$$

The absorbed power in the thermistor raises its temperature according to the mass and material constants for the glass. With W the energy stored in the glass, there is a change $\Delta W = c\Delta T$ if the power is absorbed in a time short compared to power losses through radiation from the bead and conduction along the attaching wires. The heat capacity $c = s_o m$ where s_o is the specific heat and m the mass of the bead. The loss rate is $dW_{➵} = (h\Delta T)dt$. Thus, the power balance gives

$$\frac{dW}{dt} = c\frac{dT}{dt} = P_{det} - h(T - T_o)$$

If radiation power is applied to the thermistor in a step function, the temperature rise is given by

$$h(T - T_o) = P_{det}[1 - \exp\{\frac{-ht}{c}\}]$$

If the radiated power is a delta function integrating to an absorbed radiated energy W_{det} the solution is

$$c(T - T_o) = W_{det} \exp\{\frac{-ht}{c}\}$$

Here, the temperature jumps instantly to the $W_{det}c^{-1}$. If the power is applied in a finite time τ we can subtract two step functions to produce a power pedestal such that $P_{rad}\tau = W_{rad}$, and the solution is the difference between the two step function solutions. We find, $h(T - T_o) = A(t) - A(t-\tau)$ where $A = 0$ when t, or $t-\tau$, is negative, and each function $A(x) = P_{det}[1 - \exp\{\frac{-hx}{c}\}]$. If $\tau << h^{-1}c$ then the solution is essentially a linear rise in temperature in a time τ, transitioning to an exponential delay with the time constant $h^{-1}c$.

The thermal time constants for the thermistor are listed as 1 sec in still air at 25° C and 14 msec if plunged into water. The dissipation constants are $h = 0.1$ mW/°C for still air at 25° C and 0.5 mW/°C for still water at 25° C. Since the time constant $h^{-1}c = 1$ sec, this indicates that $c = 0.1$ mW-sec/°C = 10^{-4} J/°C in still air. We can check this using the mass and specific heat of glass. Using a density of 2.5 g/cm^3 (the value for quartz) and the volume of an ellipsoid ($\frac{4}{3}\pi a_1 a_2 a_3$, with $a_1 = a_2 = 0.5\zeta$ and $a_3 = 0.5$ ➸) we find for ➸ $= 2\zeta$ a bead mass of $m = \frac{5\pi\zeta^3}{6} = 1.18 \times 10^{-4}$ grams. For a specific heat we take 1 Joule/gram/°C so the heat capacity is $c = 1.18 \times 10^{-4}$ J/°C. This is close to the value given by the time constant and dissipation constant given by the manufacture, so we will take the manufacturers values until calibrations are done.

To characterize the resistance ratio (to the resistance at 25° C) curves are published for each device. The curve below is for our thermistor, with material designation A, in which the $\text{Log}_{10}\frac{R}{R_o}$ is plotted vs. temperature. Here, R_o is the nominal 10K resistance at 25° C. The resistance drops quickly with temperature.

A bridge circuit is used to determine the resistance change in the thermistor. There are two of these thermistors in a bridge circuit, one seeing the radiation and the other covered but used for nulling any thermal drift. Each is in series with a 10K resistor, and these series pairs are in parallel across the bias voltage V_s. The nominal resistance of the thermistor without radiation is $R_o = 10$ K, so there is a voltage difference across the thermistors of a value V_d such that $\frac{V_d}{V_s} = (\frac{1}{2} - \frac{R}{R+R_o})$. This signal is amplified by the gain $G = 61.86$ giving an output voltage V_o at the digitizer of GV_d, and since $V_s = 1.2$ volts we have $V_o = 0.6G(1 - \frac{2R}{R + R_o})$. Note that if $R = R_o(1 - \varepsilon)$,

$$V_o = 0.6G\{1 - \frac{1 - \varepsilon}{1 - 0.5\varepsilon}\} \qquad \text{or for } \varepsilon << 1 \qquad V_o \approx 0.3\varepsilon G = 18.6\varepsilon$$

The various formulae here relate the radiated energy $W_{rad} = pV\tau$ (plasma volume $V = \pi a^2 L$) to the digitized voltage V_o. From P_{rad} and P_{det} we find

$$\frac{W_{rad}}{W_{det}} = 6.3aLs\zeta^{-3} \quad \text{and} \qquad W_{det} \approx c\Delta T \qquad \text{for} \quad \tau << h^{-1}c$$

The temperature rise determines the detected energy and, from the curve below, the resistance $\frac{R}{R_o}$, from which we find $W_{rad.}$ Conversely, given the digitizer voltage, we find the resistance ratio and hence the temperature rise and detected energy.

If we insert numbers into these formulae (use a = L = 50 cm, s = 0.775 cm, ζ = 0.014 inches) we find $W_{rad} = 2.71 \times 10^8\ W_{det}$. Using the heat capacity we find that $W_{det} = 1 \times 10^{-4}\ \Delta T$. For a total radiated energy of 100 kJ we would get a detector energy of 3.69×10^{-4} J and a temperature rise of 3.69 °C. For small temperature deviations the curve above is approximated by $\log_{10} \frac{R}{R_o} \approx \frac{-3\Delta T}{185}$ so the resistance would drop to 87% of R_o. Using $\varepsilon = 0.13$ gives $V_o = 2.58$ Volts.

To summarize, the total radiated energy from the plasma is

$$W_{rad} = -1.67\log_{10}\frac{R}{R_o} \quad \text{MJ} \qquad \frac{R}{R_o} = 1 - \varepsilon$$

$$V_o = 37.12\{1 - \frac{1 - \varepsilon}{1 - 0.5\varepsilon}\}$$

In the approximation $\varepsilon << 1$ we have $\log_{10}(1 - \varepsilon) \approx \frac{-\varepsilon}{\ln 10}$ so that $W_{rad} \approx \frac{1.67\varepsilon}{\ln 10}$. Then,

$$W_{rad} \approx 39\ V_o\ \text{kJ}$$

Finally, note that the current through the thermistor in the bridge circuit is approximately that of 1.2 V across 20 KΩ, and when the balancing circuit is disconnected just before the shot, this current heats the thermistor with a power $P_{therm} = I^2R = 72\ \mu W$. Using the specific heat of 10^{-4} gives a heating rate of 0.72 °C per second, and the step function response shows that after many seconds the temperature rise is $h^{-1}P_{therm} = 0.72$ °C. This drops the thermistor resistance by 2.7% and creates a voltage pedestal of 0.027 x 18.6 = 0.5 V.

Reference

K.I. Thomassen, "The SSPX Bolometer Systems", UCRL-ID-137802, Feb 2000